COMPUTATIONS OF ATMOSPHERIC ENERGY AND ITS TRANSFORMATION FOR THE NORTHERN HEMISPHERE FOR A RECENT FIVE-YEAR PERIOD

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ABSTRACT

Computations of atmospheric energy and several of its transformation terms from data extending back to October 1958 have been carried out using the National Meteorological Center's ADP analyses. From these calculations the annual variation of the atmosphere's energy cycle has been estimated. In addition, some yearly differences for the colder half of the year are described.

1. INTRODUCTION

Over the past several years the authors have been routinely computing certain energy parameters for the Northern Hemisphere from conventional tropospheric synoptic data. These parameters include the available potential energy, the kinetic energy, and also some of the transformation terms.

Fundamental to this study is the classic paper by Lorenz [14] in which the concept of available potential energy was introduced and a set of equations was derived depicting the atmospheric energy cycle. The available potential energy is a measure of the amount of energy available for conversion into kinetic energy; it can be defined as the excess of total potential energy above the amount which would exist if the isentropic surfaces were horizontal. In magnitude it amounts to less than a half percent of the total potential energy. It is produced when there is a positive spatial covariance between heating and temperature, while its transformation to kinetic energy depends upon a spatial covariance between vertical velocity and temperature.

Following Lorenz's treatment of available potential energy, the quantity was first calculated extensively in the analysis of the energetics of general circulation models by Phillips [20] and Smagorinsky [26]. Computations for the actual atmosphere over the Northern Hemisphere were also begun by a few investigators, but published values have been limited thus far to averages for four months (Van Mieghem et al. [32]), averages for one month (Saltzman and Fleisher [24]), and daily values for a 42-day period (Winston [38]). A case of a large-scale cycle of available potential energy which occurred in this latter period was studied in some detail by Winston and Krueger [39]. More recently Oort [17] has calculated available energy from time-averaged temperature data and Wiin-Nielsen [37] has presented spectral data for the available potential and kinetic energy for five months.

Computations of other energy parameters from Northern Hemisphere synoptic data were made earlier, of course. Spar [27] made calculations of kinetic, potential, and internal energy from the normal weather maps for January and July. Pisharoty [21] made a detailed study of the kinetic energy in the Northern Hemisphere on a daily basis for two months. More recently several other investigators have also calculated kinetic energy (e.g., Van Meighem et al. [32], Horn and Bryson [9], Saltzman and Fleisher [25]).

Studies of transformations between one form of energy and another have been more numerous than studies of the actual energy values themselves. Most of the aforementioned studies have dealt with both the energy values and some of the transformation terms. Computations of large-scale energy transformations from comprehensive synoptic data concentrated at first mainly on the transformations between eddy and zonal kinetic energy (Starr [28], Pisharoty [21]). Subsequently attempts were made to compute the transformation between potential and kinetic energy. Initially these were carried out by White and Saltzman [33] for an area covering part of the United States and Canada, but shortly afterward Wiin-Nielsen [34], and also Saltzman and Fleisher [24], extended these computations to cover most of the Northern Hemisphere. This became possible with the development of routine automatic data processing (ADP) analyses and baroclinic numerical prediction models that produced vertical velocity computations as a by-product. Using these ADP analyses, Wiin-Nielsen and Brown [35] also attempted to compute the diabatic heating over the Northern Hemisphere and from these they were able to compute the generation of zonal and eddy available potential energy. Their heating calculations were also used by Winston and Krueger [39] to compute energy generation and good agreement was found with actual time variations in the available energy.

Usually these various energy computations have been based upon data from the midtroposphere. During the past several years, however, several investigators have

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attempted to describe the vertical variation of several of the transformation terms. Jensen [10] has done this for the potential to kinetic energy conversion while Wiin-Nielsen, Brown, and Drake [36] and Wiin-Nielsen [37] have examined the vertical variation of the conversion between zonal and eddy available potential energy as well as that for zonal and eddy kinetic energy. Presently, more attention is also being given to the energy budget in the stratosphere ([30], [31], [22]).

A useful compilation of values for these various energy transformations, as obtained by several principal investigators of the energy budget, has recently been made by Oort [17]; this should be consulted for ready comparison of the various computations.

In the present study we have extended some of the above computations so as to describe the annual variation of atmospheric energy and its transformation for the lower troposphere. From these computations we have attempted to infer the generation of zonal and eddy available potential energy and to describe the seasonal variations and year-to-year differences in the energetics of the general circulation of the Northern Hemisphere.

2. PROCEDURE

THE ENERGY EQUATIONS

Expressions for the various quantities computed were taken from Lorenz [14] and are as follows: Available potential energy is mainly a function of the variance of temperature on constant pressure surfaces; the equations for the zonal and eddy components are

$$A_Z=\frac{1}{2}\int_0^{\bar{p}_0}\frac{1}{S\bar{T}}\overline{[T]'^2}dp \qquad (1)$$

$$A_E=\frac{1}{2}\int_0^{\bar{p}_0}\frac{1}{S\bar{T}}\overline{T^{*2}}dp \qquad (2)$$

where T is the absolute temperature, p is the pressure, $S=\Gamma_d-\bar{\Gamma}$ with Γ_d the dry adiabatic lapse rate and $\bar{\Gamma}$ the average lapse rate for the pressure surface. Here and in what follows, the square brackets denote a latitudinal average while the asterisk denotes a departure from this average. A bar indicates an area average and a prime represents a departure from this average. This latter averaging is over both latitude and longitude and is performed in the following manner:

$$\bar{x}=(\sin 90°-\sin 20°)^{-1}\int_{20°}^{90°}[x]d\sin\varphi.$$

The kinetic energy equations are:

$$K_Z=\frac{1}{2g}\int_0^{\bar{p}_0}\overline{[V]^2}dp=\frac{1}{2g}\int_0^{\bar{p}_0}\overline{[u]^2}dp \qquad (3)$$

$$K_E=\frac{1}{2g}\int_0^{\bar{p}_0}\overline{V^{*2}}dp=\frac{1}{2g}\int_0^{\bar{p}_0}\overline{([u^2]-[u]^2+v^{*2})}dp \qquad (4)$$

where g is the acceleration of gravity, V is the wind with a zonal component u and a meridional component v, which in this study were evaluated geostrophically. Note that the zonal kinetic energy is that of the mean zonal motion.

Lorenz's equations expressing the rate of change of A_Z, A_E, K_Z, K_E are:

$$\frac{\partial A_Z}{\partial t}=-C_Z-C_A+G_Z \qquad (5)$$

$$\frac{\partial A_E}{\partial t}=-C_E+C_A+G_E \qquad (6)$$

$$\frac{\partial K_Z}{\partial t}=C_Z-C_K-D_Z \qquad (7)$$

$$\frac{\partial K_E}{\partial t}=C_E+C_K-D_E, \qquad (8)$$

where C_Z is the conversion between zonal potential and zonal kinetic energy, C_E is the conversion between eddy potential and eddy kinetic energy, C_A the conversion between zonal and eddy available potential energy, C_K is the conversion between zonal and eddy kinetic energy, G_Z and G_E are respectively zonal and eddy generation of available potential energy, and D_Z and D_E are zonal and eddy dissipation terms. In this study only C_Z, C_E, and C_A have been computed and they are computed from:

$$C_Z=-\frac{R}{g}\int_0^{\bar{p}_0}\frac{1}{p}\overline{[\omega]'[T]'}dp \qquad (9)$$

$$C_E=-\frac{R}{g}\int_0^{\bar{p}_0}\frac{1}{p}\overline{\omega^*T^*}dp \qquad (10)$$

$$C_A=-\frac{c_p}{g}\int_0^{\bar{p}_0}\frac{\bar{\theta}}{\bar{\bar{T}}}\overline{\left([v^*T^*]\frac{\partial}{\partial y}+[\omega^*T^*]\frac{\partial}{\partial p}\right)\left(\frac{\Gamma_d}{S\theta}[T]'\right)}dp \qquad (11)$$

where c_p is the specific heat at constant pressure, ω is the vertical velocity in pressure coordinates, R is the gas constant for dry air, and θ is the potential temperature. C_A is essentially proportional to the meridional heat transport since the second term within the parentheses involving the vertical heat transport is small, averaging only about 3 percent of the first.[1] Consequently we have computed only the first component of C_A.

DATA AND PARAMETERS COMPUTED

The computations that we have carried out and have summarized here were made once a day at 0000 GMT during the period October 1958 through July 1963 using objectively analyzed contour heights of the 850- and 500-mb. surfaces prepared by the National Meteorological Center (NMC). Also utilized were initial vertical velocities that were obtained from the baroclinic model in use at the time. Prior to June 1962 these were based on a two-parameter model, while presently they are based upon computations from a three-level baroclinic model devised by Cressman [2].

[1] This was determined from computations for 10 days in the winter season.

Zonal and eddy components of the available potential and kinetic energies were computed for the area north of 20° N. In addition the transformation between the zonal and eddy available potential energy and the components of the potential to kinetic energy conversion were computed over the same region. The conversion between zonal and eddy kinetic energy, C_K, which has been rather extensively discussed in the literature, was not computed here. A value of 5.1° K. km.$^{-1}$, which was determined from climatological data, was used for the average lapse rate, $\overline{\Gamma}$.

3. ANNUAL VARIATION

The intensity of the general circulation, which may be measured by the kinetic energy of the atmosphere, is greatest during the colder portion of the year. Correspondingly, the fraction of the total potential energy available to drive this circulation is also greatest in the colder part of the year despite the fact that the total potential energy of the atmosphere is at a minimum [27]. This is seen in figures 1 and 2 where monthly averages of the zonal and eddy components of the available potential and kinetic energies for each of the years studied are plotted. In addition the overall average monthly values of these parameters are tabulated in table 1.

Compared with the other three terms, the variation of the zonal available potential energy during the cold season appears anomalous. In general it rises to a primary maximum in December, then drops to a minimum in January when the other three usually reach their highest values. This is followed by a rise to a second maximum in March when the remaining three have already begun their springtime declines. Apparently the major energy cycle of the year, which occurs during January, is sufficiently intense to counteract the very strong winter generation of zonal available potential energy.

The times of most rapid energy change are from August to October and from March to June. It is interesting that the year-to-year variability of monthly values (particularly the zonal available potential energy) during much of the springtime decline seems to be much smaller than during the autumn buildup.

Table 1.—*Average monthly values of zonal and eddy available potential and kinetic energy and three conversion terms. All for layer 850–500 mb.*

	kj.m.$^{-2}$				watts m.$^{-2}$		
	A_Z	A_E	K_Z	K_E	C_Z	C_E	C_A
January	1602	530	171	273	−0.38	1.88	2.47
February	1640	459	167	249	−.30	1.56	2.06
March	1710	366	144	219	−.47	1.41	1.82
April	1431	274	100	191	−.23	1.04	1.34
May	1038	210	68	154	−.39	.67	.79
June	707	168	49	122	−.16	.36	.35
July	506	140	38	95	−.09	.22	.24
August	614	130	45	98	−.17	.31	.34
September	963	166	65	129	−.16	.70	.80
October	1335	276	93	181	−.36	1.09	1.36
November	1599	379	127	206	−.52	1.42	1.79
December	1695	438	162	240	−.49	1.79	2.14
Annual average	1296	295	104	180	−.31	1.04	1.29

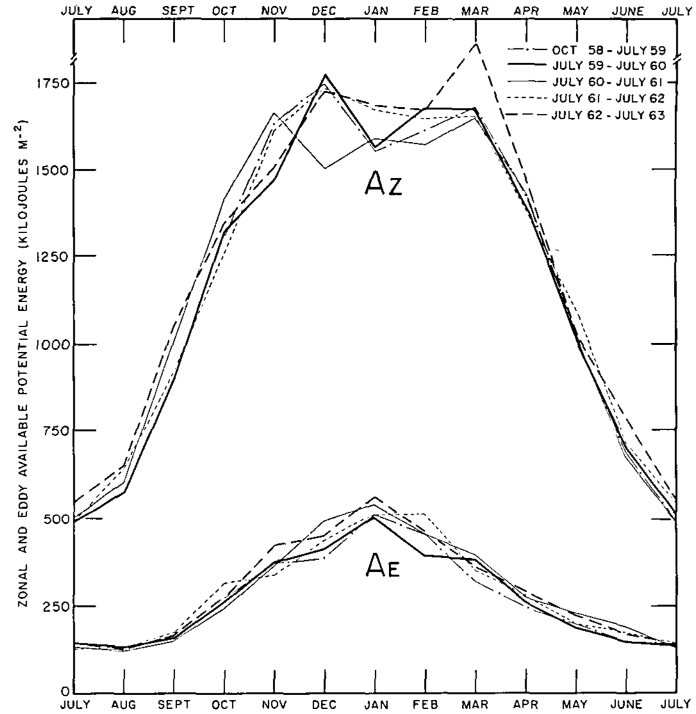

Figure 1.—Annual variation of zonal (A_Z) and eddy (A_E) available potential energy in the layer 850–500 mb. for five consecutive years, October 1958–July 1963.

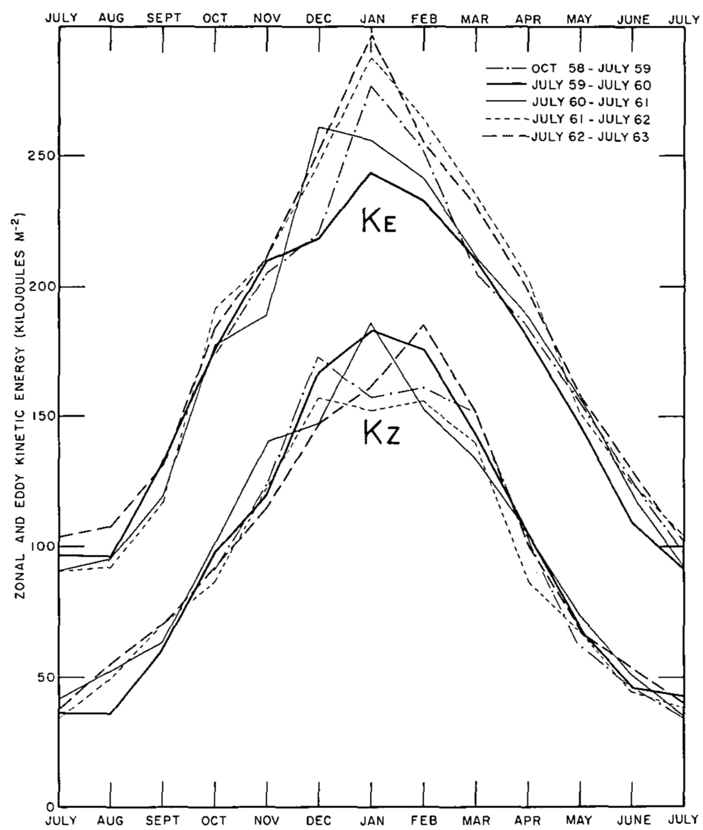

Figure 2.—Annual variation of zonal (K_Z) and eddy (K_E) kinetic energy in the layer 850–500 mb. for five consecutive years, October 1958–July 1963.

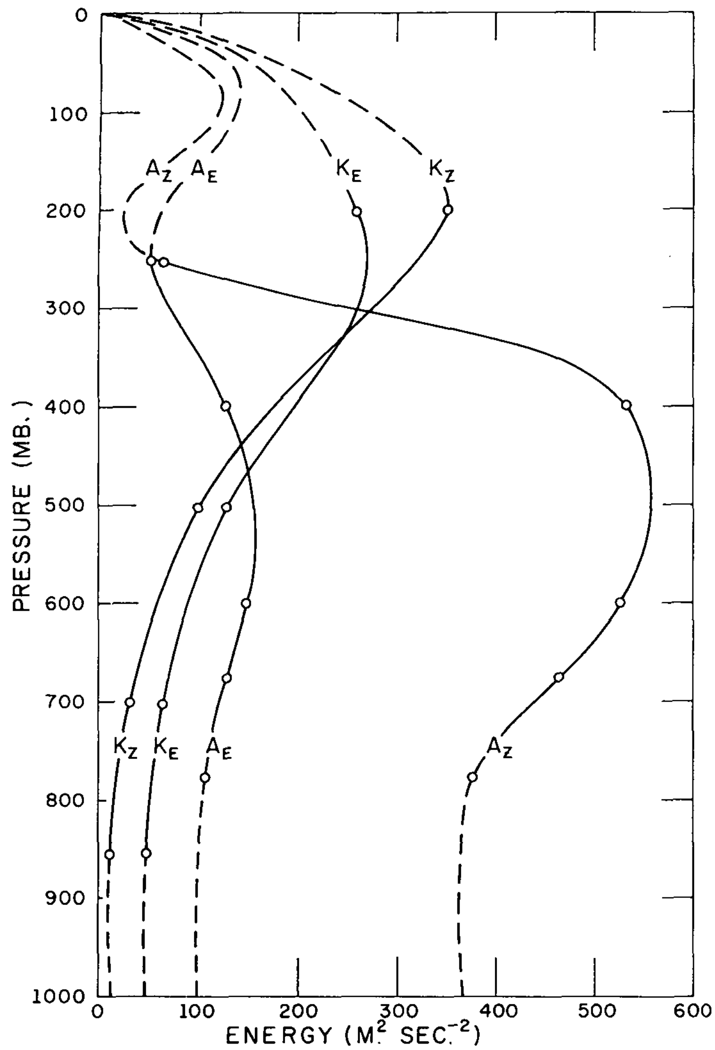

FIGURE 3.—Vertical variation of zonal and eddy available potential and kinetic energy (per unit mass) for ten cases. Above 200 mb. and below 850 mb. it was necessary to extrapolate.

Inspection of the magnitudes of the energy components in figures 1 and 2 and in table 1 readily shows that the zonal available potential energy is by far the largest of the four components, averaging about twice the sum of the other three. The eddy available potential energy on the average has a magnitude of about 23 percent of the zonal available potential energy, the eddy kinetic energy about 14 percent, and the zonal kinetic energy about 8 percent. For comparative purposes it is of interest to point out that the maximum monthly value of zonal available potential energy in table 1, 1710 kj.m.$^{-2}$, is equivalent to the kinetic energy of a uniform wind of approximately 60 kt. in the layer 850–500 mb.

The natural question arises at this point as to how much of the energy of the Northern Hemisphere is in this 850–500-mb. layer. In an attempt to answer this we have computed the vertical distribution of the available potential and kinetic energies for 10 days chosen between November and March during the years 1961–63 (fig. 3). The data used were the ADP analyses for the levels 850, 700, 500, 300, and 200 mb. prepared by the National Meteorological Center. Below 850 mb. and above 200 mb., however, it was necessary to extrapolate using other estimates as a guide.

Integrating over pressure we obtain 1355 kj.m.$^{-2}$ for the 10-day average zonal kinetic energy with 148 kj.m.$^{-2}$ or 11 percent in the layer 850–500 mb. For the eddy kinetic energy the integrated value is 1398 kj.m.$^{-2}$ with 19 percent or 266 kj.m.$^{-2}$ in this layer. The zonal available potential energy, on the other hand, varies inversely in the vertical to the kinetic energy. It is large in the troposphere up to about 400 mb. and drops off very rapidly above, reaching a minimum around 200 mb. where the kinetic energy is greatest. Integrating throughout the depth of the atmosphere, we get 3479 kj.m.$^{-2}$ with 1652 kj.m.$^{-2}$ or 47 percent in the 850–500 mb. layer. For the eddy available potential energy figure 3 gives 1142 kj.m.$^{-2}$ with 40 percent or 462 kj.m.$^{-2}$ in the layer 850–500 mb. Thus the ratio of available potential to kinetic energy is 1.7. From this analysis it is estimated that the annual average energy for the 1000-mb. depth of the atmosphere is about 2720 and 730 kj.m.$^{-2}$ for the zonal and eddy available potential energy respectively, and 950 kj.m.$^{-2}$ for both the zonal and eddy kinetic energy. More extensive studies of the vertical distribution should of course be carried out, and it should be kept in mind that it is risky to attempt to infer the vertical energy integral on a daily basis from only 850–500-mb. data.[2]

The transformation from zonal to eddy available potential energy is also greatest in winter (fig. 4 and table 1). It is notable that C_A changes by an order of magnitude from summer to winter. Since this term is largely dependent on the northward heat transport the annual variation of C_A strongly resembles the annual course of poleward heat transport (cf. fig. 2 of Haines and Winston [6]). This conversion process is sufficiently intense to deplete completely the zonal available potential energy in the layer in about 8 days during winter if there were no energy source present. In summer, however, this depletion would take 25 days; this may be interpreted as indicative of the lower rate of generation required to maintain the zonal available potential energy in summer.

The distribution of C_A in the vertical has been computed for the month of January 1962 by Wiin-Nielsen, Brown, and Drake [36], and their results are graphed in figure 5. Here it appears that C_A reaches a maximum in the mid-troposphere and decreases very rapidly above 400 mb., a variation resembling that of the zonal available potential energy (fig. 3). From their computations they obtain a value of 5.55 watts m.$^{-2}$ for C_A integrated through the entire depth of the atmosphere, while for the layer 850–

[2] These computations are in good agreement with more extensive computations (in the vertical) we have carried out since this study was completed, as well as with some very recent calculations of Wiin-Nielsen [37] to which the reader is referred.

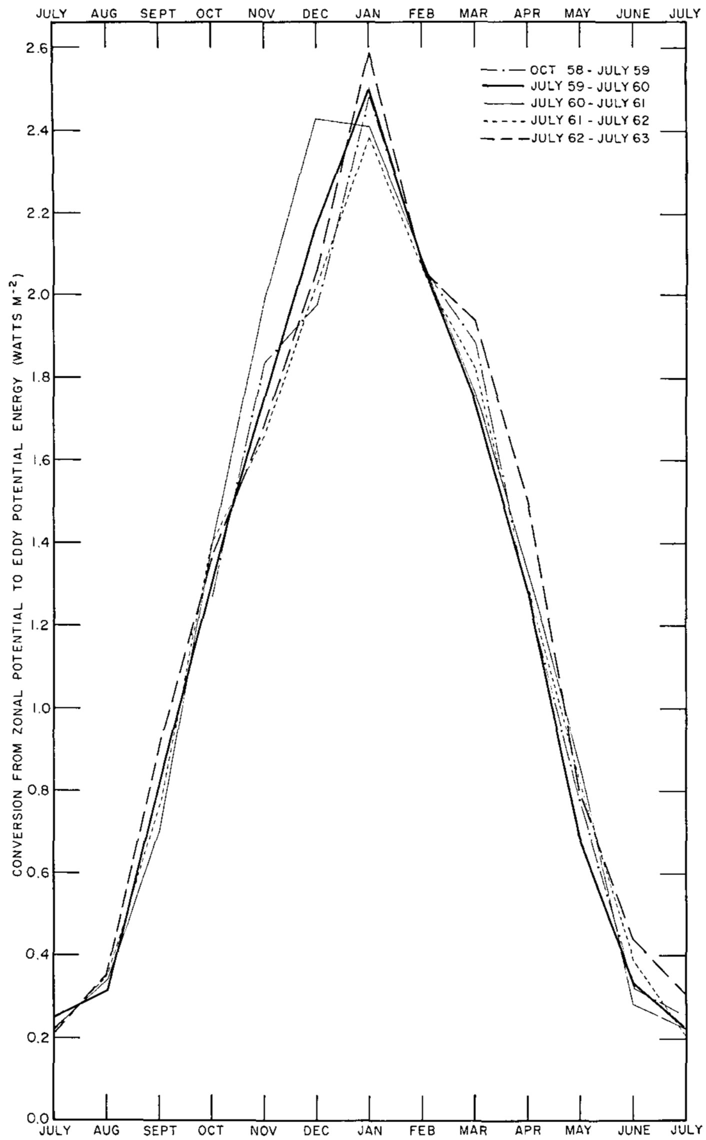

FIGURE 4.—Annual variation of the transformation between zonal and eddy available potential energy (C_A) in the layer 850–500 mb. for five consecutive years, October 1958–July 1963.

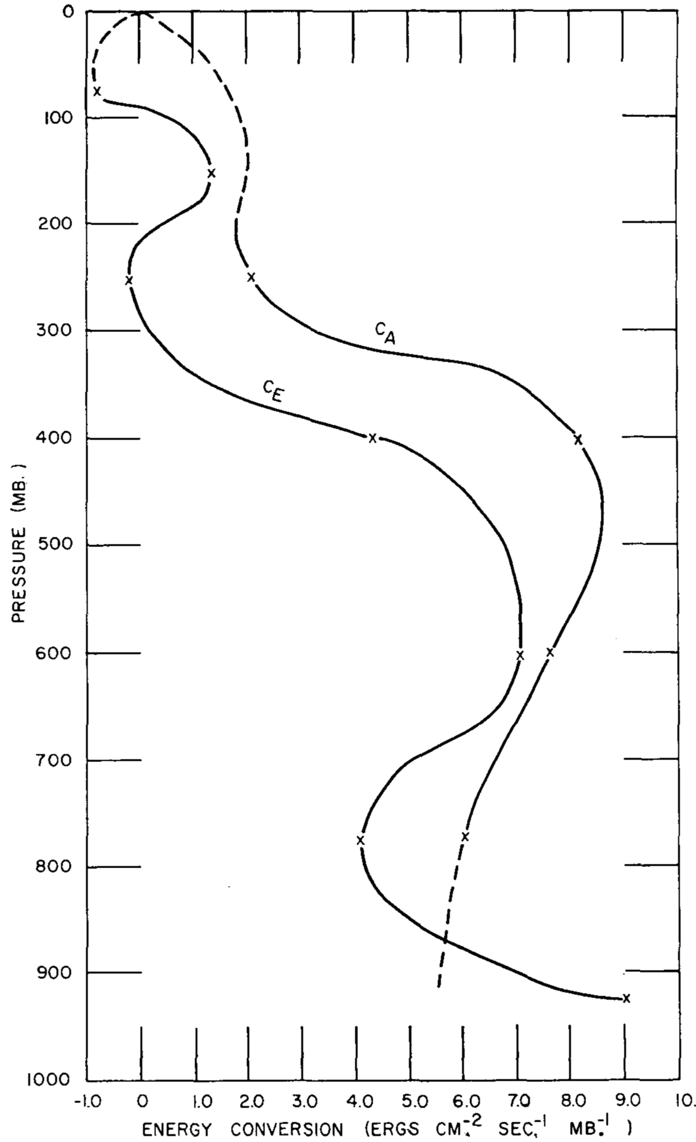

FIGURE 5.—Vertical variation of C_A for January 1962 (from Wiin-Nielsen, Brown, and Drake [36]) and C_E for January 1958 (from Jensen [10]).

500 mb. they obtain slightly less than half this value or 2.41 watts m.$^{-2}$ Assuming that this relationship between the vertically integrated value and the corresponding value of C_A for the layer 850–500 mb. holds on the average for all months of the year, we have estimated the annual variation of C_A for the entire column from our mean monthly values between 850 and 500 mb. These values for the various months and also seasonal and annual averages are given in table 2. The seasonal and annual means will be utilized further in a later section of this paper.

The remaining transformation terms that were computed were the zonal (C_Z) and eddy (C_E) conversions between potential and kinetic energy. As indicated earlier these were computed using the NMC-prepared

TABLE 2.—*Estimates of average monthly values of conversion terms* C_Z, C_E, C_A *and generation terms* G_Z *and* G_E *for the entire atmosphere (units: watts* m^{-2}*)*

	C_Z	C_E	C_A	G_Z	G_E
January	−0.81	4.00	5.70	4.86	−1.69
February	−.64	3.32	4.75	4.14	−1.51
March	−1.00	3.00	4.20	3.12	−1.29
April	−.49	2.21	3.09	2.35	−.96
May	−.83	1.42	1.81	.68	−.44
June	−.34	.77	.82	.26	−.08
July	−.19	.47	.56	.34	−.11
August	−.36	.66	.79	.61	−.12
September	−.34	1.49	1.84	1.80	−.28
October	−.77	2.32	3.12	2.62	−.70
November	−1.10	3.02	4.10	3.15	−1.00
December	−1.04	3.81	4.93	3.89	−1.04
Annual	−.66	2.21	2.98	2.32	−.77
Winter	−.83	3.71	5.13	4.30	−1.42
Spring	−.77	2.21	3.04	2.05	−.91
Summer	−.30	.63	.72	.40	−.10
Autumn	−.74	2.28	3.02	2.52	−.66

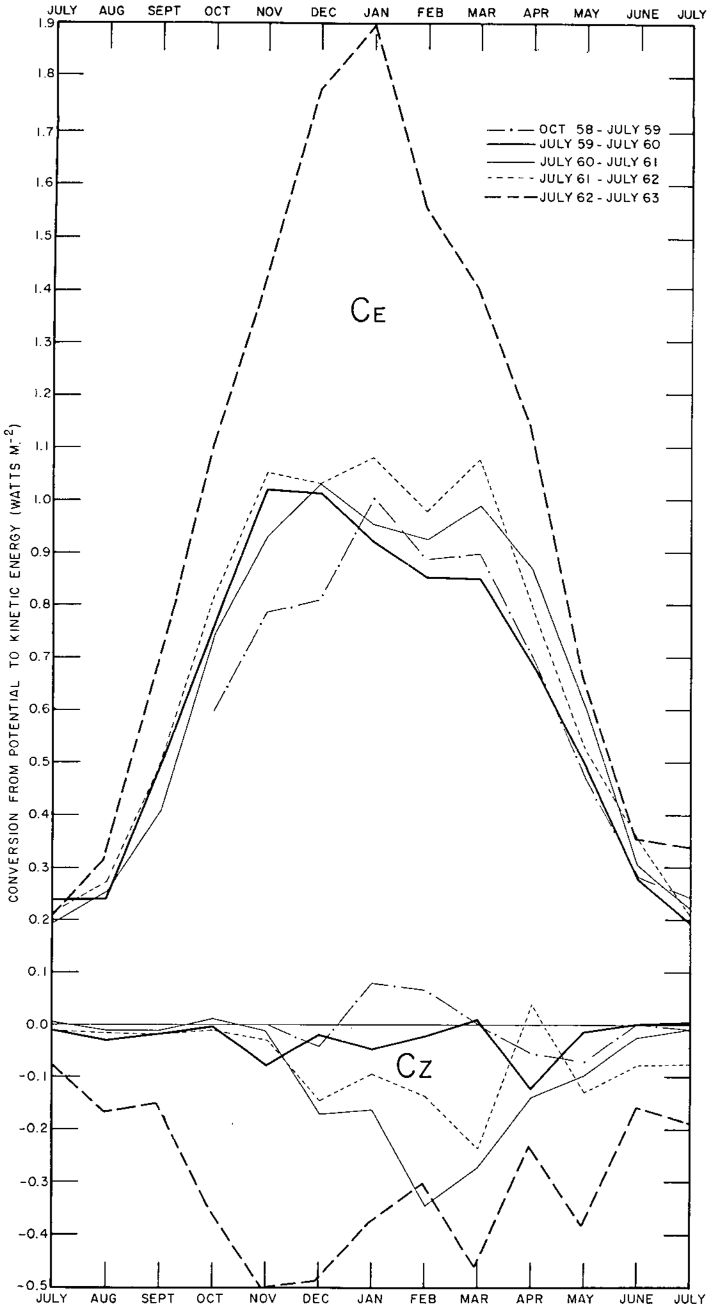

FIGURE 6.—Annual variation of the zonal (C_Z) and eddy (C_E) conversion between potential and kinetic energy in the layer 850–500 mb. for five consecutive years, October 1958–July 1963. The year 1962–63 is considered most representative.

initial vertical velocities which, prior to June 1962, were obtained from a two-parameter baroclinic model, and more recently were obtained from a three-level model [2]. Since the changeover both C_Z and C_E have averaged larger in magnitude, with C_E averaging as much as 70 percent higher in winter. The differences are strikingly apparent in figure 6. Here the two-parameter model gives four annual curves for C_E which are quite similar and which have an average cold season value of about 1 watt m.$^{-2}$ Compared with the more recent three-level calculations, these cold season values appear truncated, and one gets the impression that the two-parameter model formerly used by the National Meterological Center was incapable of producing a value of C_E much larger than 1 watt m.$^{-2}$

While these vertical velocities have been used in several studies of the potential-kinetic energy conversion [24], [34], [39], they have been criticized by Palmén [18] as giving values of C_E that are too small. On the basis of studies of frictional dissipation, he has estimated that throughout the entire depth of atmosphere in winter there should be 5–8 watts m.$^{-2}$ converted from potential to kinetic energy. Lettau [13] has estimated a value of approximately 5 watts m.$^{-2}$ which is comparable to the values obtained over North America by White and Saltzman [33].[3] These values seem more reasonable and, therefore, we have accepted the three-level calculations as more representative and have listed these in table 1 as "typical" for values of C_E and C_Z.

These recent values of C_E in the layer 850–500 mb. have an annual variation similar to but slightly less than C_A. Even on a day-to-day basis our data (not presented here) show that C_E and C_A tend to vary together—a relationship suggested by Kuo [11] and noted in a previous study [39]. This relationship is clearly demonstrated in figure 7 where 10-day averages of C_E and C_A for the period August 1962 to July 1963 have been plotted; the two conversion terms are almost perfectly correlated (0.98).

The vertical distribution of C_E has been studied by Jensen [10] for the month of January 1958, and his results have also been graphed in figure 5. Except for the friction layer the largest values again occur in the mid-troposphere and decrease very rapidly above. For an integrated value throughout the entire atmosphere Jensen obtained 4.28 watts m.$^{-2}$, while a value of 2.02 watts m.$^{-2}$ was obtained for the layer 850–500 mb. indicating that slightly less than half of this conversion also takes place within the layer 850–500 mb. Using the ratio between Jensen's integrated value of C_E for the 1000-mb. depth of the atmosphere and his value in the layer 850–500 mb. we have adjusted our monthly averaged 850–500 mb. values to obtain an estimate of the annual variation of C_E for the column as was done for C_A. These values are shown in table 2. They will be discussed in more detail in the next section as part of the treatment of the atmospheric energy cycle.

In winter the C_E term for the 850–500-mb. layer is large enough to deplete completely the eddy potential energy in about 3 days. Combined with C_Z it is sufficient to increase the kinetic energy in this layer from zero to the winter maximum of 444 kj.m.$^{-2}$ also in about 3 days, a value equal to Haurwitz's [7] estimate of the time required by friction to deplete completely the kinetic energy. However, since most of the atmosphere's kinetic energy occurs above the 500-mb. level, this figure is not

[3] It should be noted that White and Saltzman used the adiabatic method to compute their vertical velocities, but obtained the required thickness tendencies from a two-parameter baroclinic model. Whether this method would result in too small a potential to kinetic energy conversion when extended to cover the Northern Hemisphere is not known.

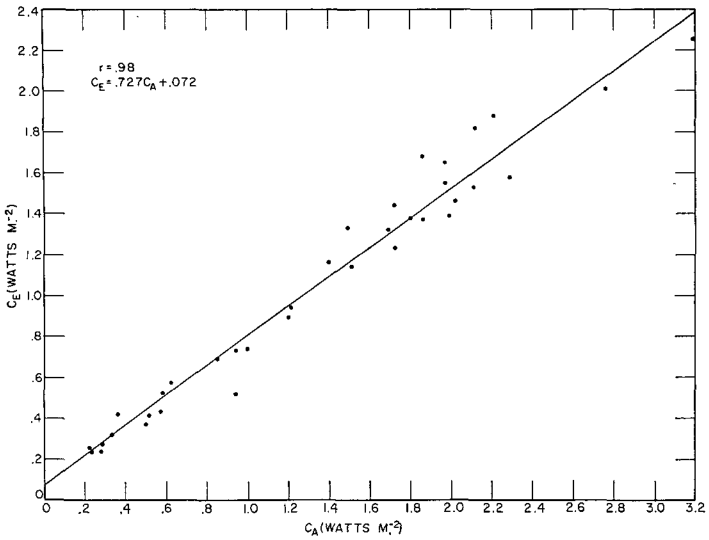

FIGURE 7.—Relationship of 10-day averages of C_E and C_A for the layer 850–500 mb. for the year 1962–63.

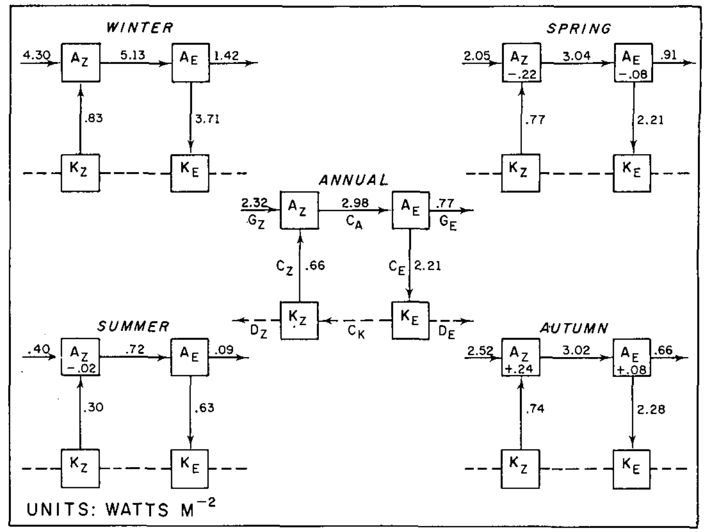

FIGURE 8.—Estimate of the annual and seasonal energy transformations, including G_Z and G_E, for the entire atmosphere north of 20° N. All values are in watts m.$^{-2}$ Figures 3 and 5 were used to estimate these values.

representative of the entire atmosphere, and when this is considered a value of 10 days is obtained. This compares with Wiin-Nielsen's [37] value of 13 days.

The term C_Z is mainly negative and tends to vary inversely as C_E and C_A (fig. 6 and table 1). Estimates of the pressure integrated value were made using data only for the latest year (1962–63) and using the same relation as for C_E above. These are also tabulated in table 2. This term is a measure of the kinetic energy production of the mean meridional circulation, and since it is negative indicates a reverse circulation or transformation from zonal kinetic energy to zonal potential energy. Because our computations are for the area north of 20° N., C_Z here primarily represents a measure of the Ferrel cell and is therefore not representative of the transformations by the meridional circulation for the entire Northern Hemisphere. We can estimate this value by using data from Palmén, Riehl, and Vuorela's [19] study of the meridional cell in the Tropics. For the area between the equator and 20° N. they obtain a kinetic energy production from the Hadley cell of +2.1 watts m.$^{-2}$ which, when combined with our winter value of −0.83 watt m.$^{-2}$ for the area north of 20° N. gives +0.17 watt m.$^{-2}$ for the Northern Hemisphere. Starr's [29] estimate for this term is about −0.1 watt m.$^{-2}$

4. GENERATION OF AVAILABLE POTENTIAL ENERGY AND THE ATMOSPHERIC ENERGY CYCLE

Using the computations just described and equations (5) and (6) we have also estimated the zonal and eddy generation of available potential energy (G_Z and G_E respectively). This was done using the monthly, seasonal, and annual values for the conversion terms tabulated in table 2 and centered time variations in available potential energy. The resulting values for the generation of available potential energy are tabulated in table 2. In addition, seasonal and annual values of all these five terms are presented in the energy cycle schematics of figure 8.

For G_Z the computations indicate an order of magnitude variation from summer to winter with an annual average of 2.32 watts m.$^{-2}$ While values for spring and fall are close to this average annual they are somewhat larger during the fall. As an estimate for the entire Northern Hemsiphere these values are probably too small and should agree more closely in magnitude with C_A. This is due to the fact that our values of C_Z, as indicated previously, do not include the contribution from the Hadley cell which would tend to decrease C_Z. If this is the case, G_Z could be as high as 5.7 watts m.$^{-2}$ in January. For comparison, Wiin-Nielsen and Brown [35] obtained a value for G_Z of 5 watts m.$^{-2}$ for January 1959, while Lettau [12] obtained about 2 watts m.$^{-2}$ for an estimate of the average annual value.

The estimates of the eddy generation, G_E, also undergo a wide variation between summer and winter, but the values are always negative (i.e., degeneration). While the value for January is only about half of Wiin-Nielsen and Brown's [35] estimate of −3.5 watts m.$^{-2}$, the average annual value is close to more recent calculations carried out by Brown [1]. Since our values of G_E mainly result from a difference between C_A and C_E, which are similar in magnitude, they are less certain than G_Z. Conceivably C_E would be larger if the effects of condensation could be incorporated in calculations of vertical motion and this in turn could make G_E less negative or even positive at certain times of the year. This is suggested by a study by Clapp [3] who, by combining the various components of the atmospheric heat balance, obtained a winter value for G_E that was positive, although admittedly very small.

Although we have not computed the transformation between eddy and zonal kinetic energy, C_K, several studies indicate that it is small and averages only about -0.1 to -0.4 watt m.$^{-2}$ (thus indicating a transfer from eddy kinetic to zonal kinetic energy) [28], [21]. This means, as Saltzman [23] has pointed out, that the bulk of the kinetic energy dissipation occurs in the eddy component and should average only slightly less than the value for C_E. On this basis the average annual dissipation is less than 2.21 watts m.$^{-2}$ and is comparable to the amount of kinetic energy dissipated in the Ekman layer according to estimates by Haurwitz [7] and Pisharoty [21]. With an average effective solar radiation of 228 watts m.$^{-2}$ (albedo=35 percent) this represents an efficiency of only 1 percent.

Seasonally our data suggest that the kinetic energy dissipation should range from about 0.5 watt m.$^{-2}$ in summer to nearly 4 watts m.$^{-2}$ in winter. The winter estimate is quite similar to results obtained by Lettau [13] which range from about 3 to 6 watts m.$^{-2}$ over North America and the Atlantic, but it is somewhat less than Palmén's estimate of 5–8 watts m.$^{-2}$ The value of 10 watts m.$^{-2}$ obtained by Holopainen [8] for the British Isles is probably quite typical of that region during winter, but seems too high to be a representative average for the Northern Hemisphere.

A comparison of our annual average energy cycle (fig. 8) with corresponding calculations from the general circulation experiments of Phillips [20] and Smagorinsky [26] is also of interest. Such a comparison can be obtained from table 3 where the agreement is seen to be quite satisfactory for G_Z, C_A, and C_E, but less so for G_E and C_Z. The estimates of G_E are not really comparable however, since Phillips did not attempt to account for this eddy generation, and Smagorinsky only partially included the heating that would give rise to such effects. Of the three computations of C_Z, Smagorinsky's value is probably the most reasonable since it includes the effects of a Hadley circulation. Also of interest are the large values of C_K in the numerical experiments as compared with the estimate of Saltzman cited earlier. Because of this the eddy dissipation in the experiments is much smaller than C_E and there is correspondingly more dissipation in the mean zonal flow.

The zonal energy components we have computed average less, while the eddy energy components average larger, than corresponding terms computed from the model experiments. Our values for A_Z and K_Z, for example, are about a third of Smagorinsky's, while in contrast A_E and K_E are about three times as large as his values (table 4).

TABLE 3.—*Comparison of energy cycles of Smagorinsky and Phillips with that obtained in this study.* (*Values in watts m.*$^{-2}$)

	G_Z	G_E	C_A	C_E	C_Z	C_K	D_Z	D_E
Smagorinsky	3.52	−0.10	2.92	2.49	−0.10	−1.23	1.27	1.53
Phillips	2.48	.00	3.54	3.54	− .40	−1.51	.97	.91
This study (table 2)	2.32	− .77	2.98	2.21	− .66	------	------	------

TABLE 4.—*Comparison of Smagorinsky's values of zonal and eddy available potential and kinetic energy with those obtained from this study.* (*Units kj. m.*$^{-2}$)

	A_Z	A_E	K_Z	K_E
Smagorinsky	9600	204	2780	358
This study	2720	730	950	945

5. YEAR-TO-YEAR DIFFERENCES IN THE COMPUTED ENERGETICS

Thus far we have concentrated mainly on the average annual variation of atmospheric energy. However, there are some interesting yearly differences, particularly during winter. These are seen not only in the monthly mean graphs of figures 1, 2, and 4, but also in figures 9, 10, and 11 where the variations of 10-day averages of A_Z, A_E, K_E, K_Z, and C_A for the period from October 1958 to July 1963 are shown.

One of the more unusual winters was that of 1960–61. During this season A_Z reached its primary maximum in November instead of December, and was followed by two more major cycles before the normal seasonal decline set in during March (figs. 1 and 9). The primary cycle was associated with early maxima in both K_E and C_A during December followed by January values averaging slightly lower (figs. 2 and 4). The cycle began in November with a rise of zonal available potential energy to a 10-day average value of 1920 kj. m.$^{-2}$ (fig. 9) followed by a very sharp drop over a period of about 20 days to an unusually low value (for winter) of 1335 kj. m.$^{-2}$ This minimum coincided rather closely with a period of low zonal index and strong subtropical westerlies over the western half of the Northern Hemisphere (Gelhard [5]). During the 10 days preceding this minimum in A_Z, i.e., the period of greatest drop in A_Z, a maximum of heat transport and of C_A occurred (fig. 10) which reached a 10-day average of 2.9 watts m.$^{-2}$ Markedly increased values of A_E accompanied this large peak in C_A. Recovery of A_Z from this minimum was fairly rapid and by early January it had reached a second maximum that was followed by even greater values of K_E as well as a maximum this time in K_Z (fig. 11). The third major maximum in A_Z was reached early in March as the remaining parameters were already trending downward. Such a maximum in A_Z at this time of year is rather typical of our data. However, the response of the other parameters following this maximum usually is small and apparent only from the daily observations.

Some measure of the variability just described is given by the standard deviations of the daily values of the energy parameters for each month (table 5). These were quite large through most of this cold season and during

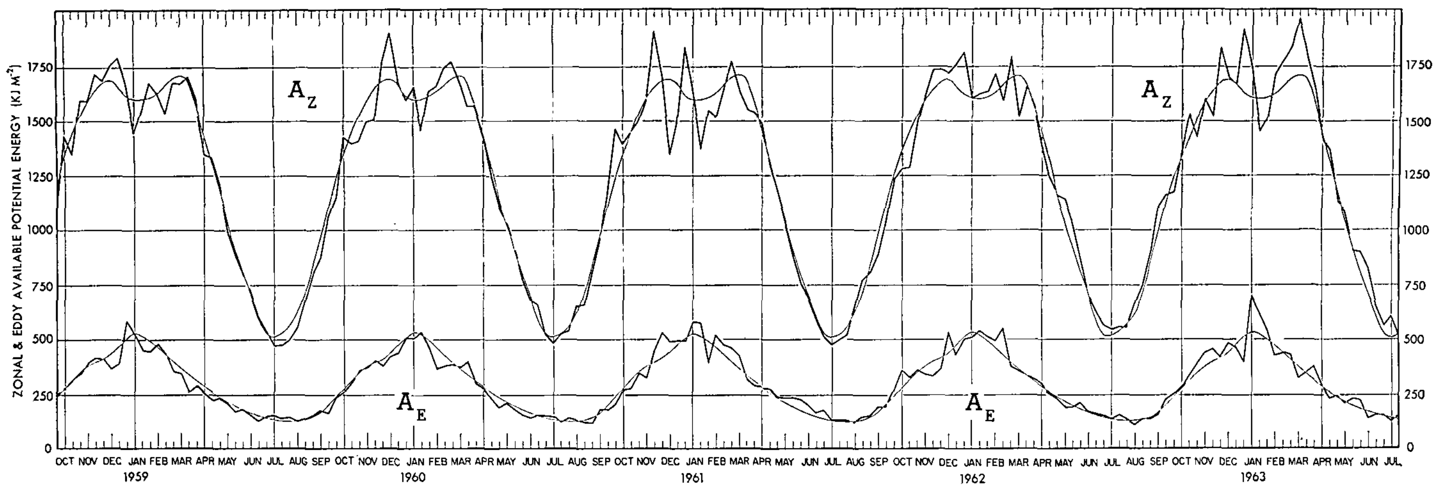

FIGURE 9.—Variation of 10-day averages of zonal (A_Z) and eddy (A_E) available potential energy for the layer 850-500 mb. (heavy curve) for the period October 1958–July 1963. The light curve is the same for each year and represents averages of the monthly values for the five years of data (table 1).

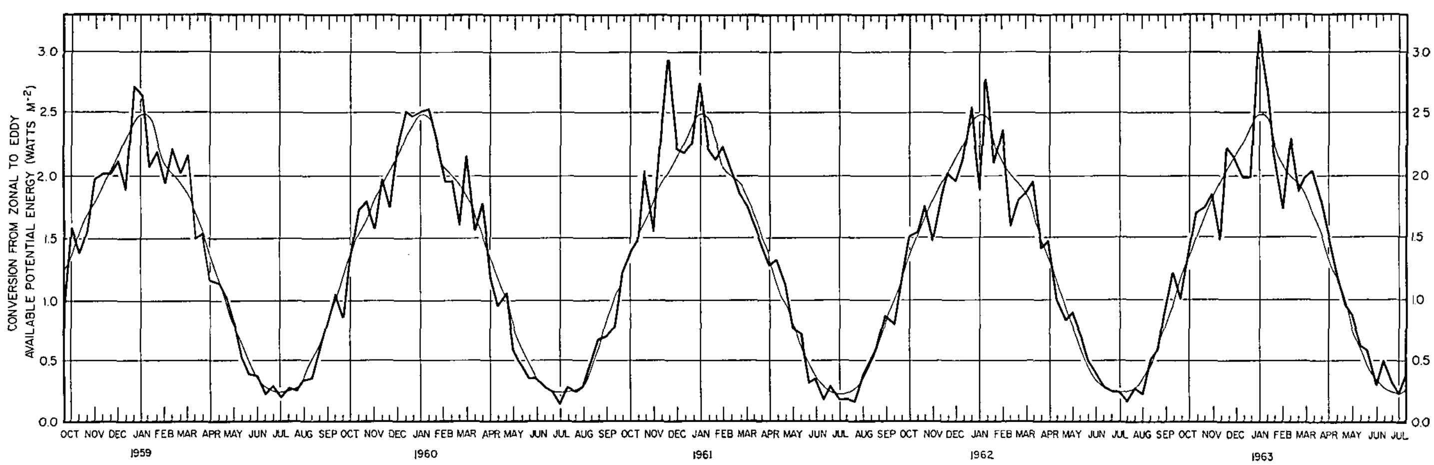

FIGURE 10.—Variation of 10-day averages of the conversion between zonal and eddy available potential energy for the layer 850-500 mb. (heavy curve) for the period October 1958–July 1963. The light curve is the same for each year and is obtained from table 1.

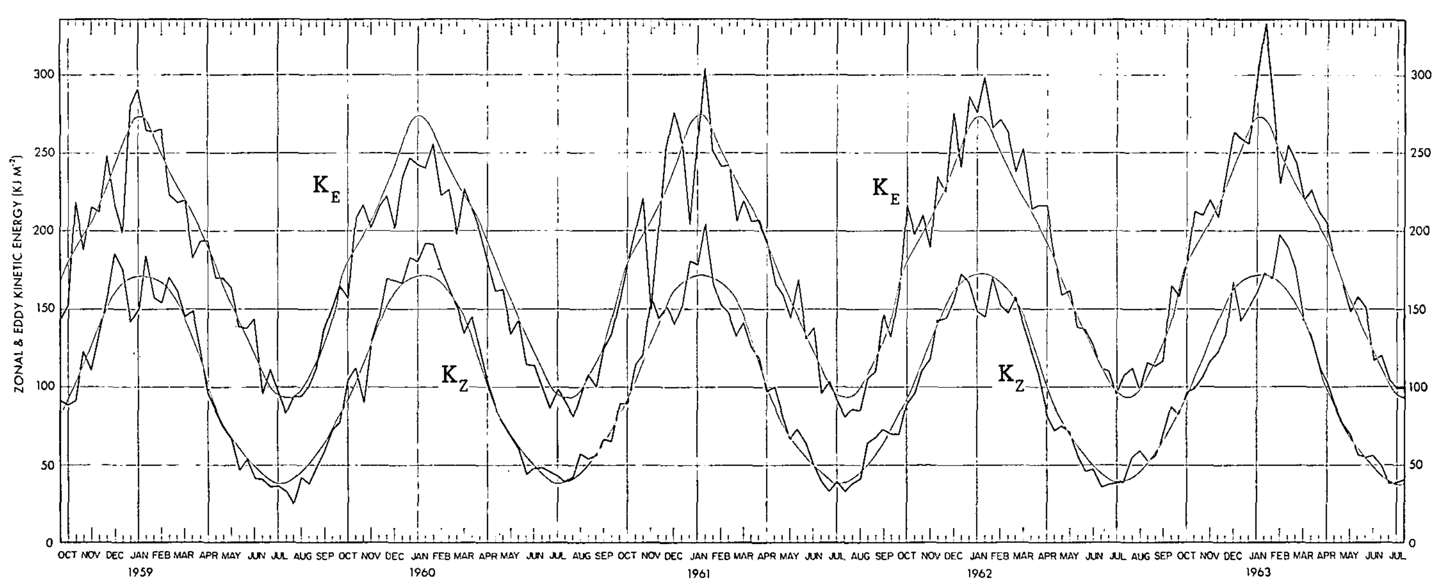

FIGURE 11.—Variation of 10-day averages of zonal (K_Z) and eddy (K_E) kinetic energy for the layer 850–500 mb. (heavy curve) for the period October 1958–July 1963. The light curve is the same for each year and is obtained from table 1.

TABLE 5.—*Standard deviations (kj. m.$^{-2}$) of daily values of zonal and eddy available potential and kinetic energies (layer 850–500 mb.)*

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
			A_Z			
1958–59	147	84	79	187	106	64
1959–60	149	67	108	139	70	108
1960–61	91	205	193	216	103	117
1961–62	66	115	83	130	97	135
1962–63	164	110	127	222	143	122
1963–64	143	76	162	140	73	180
			A_E			
1958–59	41	39	35	67	37	56
1959–60	37	45	43	65	63	57
1960–61	36	71	45	81	71	64
1961–62	56	50	93	47	53	45
1962–63	44	69	63	141	76	63
1963–64	32	53	60	43	48	45
			K_E			
1958–59	39	17	25	34	28	24
1959–60	24	14	20	22	18	24
1960–61	23	32	25	41	29	24
1961–62	57	27	32	28	29	31
1962–63	36	28	40	44	29	21
1963–64	19	32	33	29	21	20
			K_Z			
1958–59	11	14	22	23	12	12
1959–60	21	29	16	15	19	13
1960–61	14	19	14	16	12	11
1961–62	17	16	17	19	16	18
1962–63	11	15	18	17	19	22
1963–64	17	25	27	10	19	33

January 1961 were rather high for all but the zonal kinetic energy.

The following winter (1961–62) the variability was much less with standard deviations for A_Z, A_E, and K_E during January, averaging considerably less than the previous year. While C_A (and the heat transport) averaged unusually low in magnitude (fig. 4), K_E averaged fairly high (fig. 2). The primary cycle in A_Z was a weak one (fig. 9). It began early in January, after a December of little variation. At this point C_A (fig. 10), which briefly had risen to an average of approximately 2.6 watts m.$^{-2}$ early in the month, dropped to 1.8 watts m.$^{-2}$ during the next 10 days, thus apparently preventing any further decline in A_Z. A period of increased C_A later in January appears to have had little effect on A_Z, although K_E reached its maximum during this period (fig. 11).

The severity of the winter of 1962–63, particularly during the month of January, is indicated by the very high values of K_E and C_A (figs. 2, 4). While A_Z averaged about the same as the previous winter (fig. 1), it was subject to greater variability. This is seen in figure 9 and also table 5 where a very high standard deviation is indicated for January. Similarly, standard deviations for A_E and K_E were also unusually large. The major energy cycle of the season began early in January (after a weaker cycle during December) with an average drop in A_Z of about 430 kj.m.$^{-2}$ in 20 days. This was accompanied by a sharp rise in A_E and C_A (fig. 10) to extremely high values during mid-January, and in K_E toward the end of the month (fig. 11). During this period extreme daily values of 4.77 and 3.28 watts m.$^{-2}$ were recorded for C_A and C_E on January 22, which represent approximately 11.0 and 7.8 watts m.$^{-2}$ for the entire column. Following a sharp decline in K_E from its peak value, K_Z reached a very strong maximum in mid-February, at a time when A_Z was already on the way up to a final maximum. This unusually high maximum in A_Z occurred during March as the other terms were undergoing their large seasonal declines. Evidently, the level of the maximum in A_Z does not necessarily determine the intensity of the subsequent energy cycle. Yet, interestingly, while A_Z was above average during March, C_A and K_E were also above average during March and during April as well (figs. 9, 10, 11).

The energetics for the winter of 1963–64 were unique, but since these data were obtained after our figures were drafted they are not included in any of the diagrams discussed thus far. They are of sufficient interest, however, to warrant some comment. In general 1963–64 resembled the winter of 1961–62 in that it was also characterized by a weak energy cycle and small variability. Reflecting this weak energy cycle, C_A averaged abnormally low during January with a monthly mean of only 2.14 watts m.$^{-2}$ and along with C_E did not reach its cold season maximum until February. Surprisingly, the January minimum in A_Z did not occur, but instead A_Z continued to rise throughout the winter to an abnormal monthly average of 2000 kj.m.$^{-2}$ during March.

Further comparison of the past four Januarys, including 1964, is given in figure 12 where the latitudinal variation of heat transport is plotted. The contrast between January 1963 and 1964 is particularly striking since at all latitudes from 20° to 60° N. the transport was appreciably greater during January 1963. At 45° N., for example, it was 25 percent larger, while at 35° N. it was 55 percent larger. This abnormal transport was responsible for a stronger heat flux convergence (fig. 13) around 60° N. (equivalent to a warming of 1.6°C. day^{-1}), and also a stronger heat flux divergence near 32° N. (equivalent to a cooling of 1.5°C. day^{-1}). During both January 1962 and 1964 the heat flux divergence was correspondingly weaker.

Previously it was suggested that since the contribution of the meridional circulation was small, C_A should approximately equal the zonal generation of available potential energy, G_Z. If this is the case, our data indicate that G_z was about 25 percent greater in January 1963 than in January 1964 (4.9 watts m.$^{-2}$ vs. 6.1 watts m.$^{-2}$ for the 1000-mb. depth of the atmosphere). This in turn implies a larger meridional heating gradient during January 1963 than during January 1964.

6. SUMMARY

The annual variations of available potential and kinetic energy, as well as three of the transformation terms for the lower troposphere, have been described. The computations indicate that, while the most intense energy cycle occurs during January, there are interesting yearly differences. January 1963 with its unusually intense energy cycle is particularly noteworthy. Also of interest

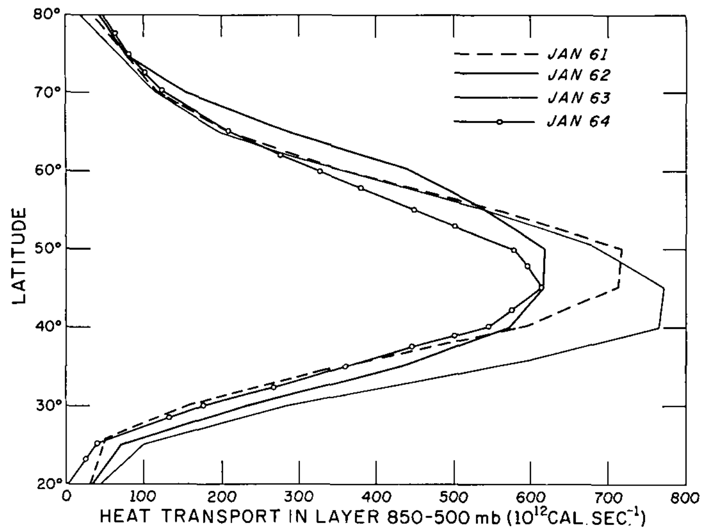

FIGURE 12.—Latitudinal variation of poleward sensible heat transport in the layer 850-500 mb. for four consecutive Januarys, 1961–64.

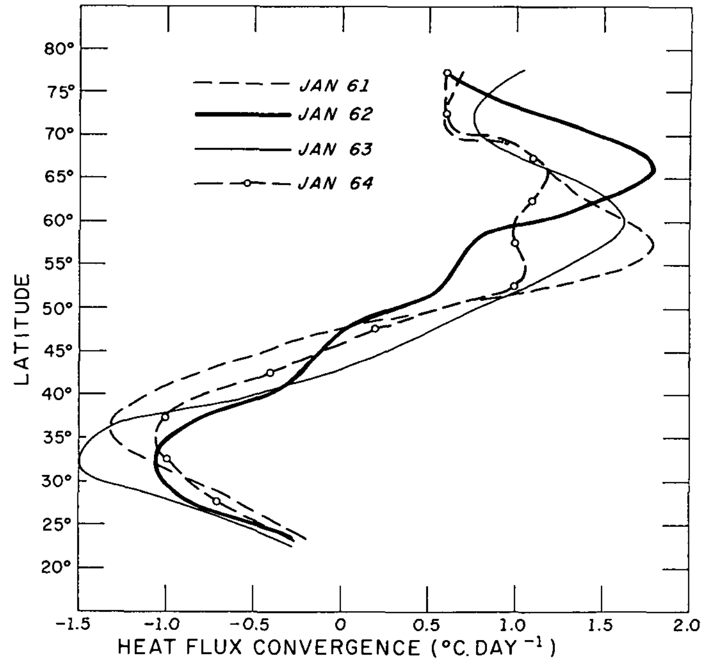

FIGURE 13.—Latitudinal variation of the sensible heat flux divergence in the layer 850–500 mb. for four consecutive Januarys, 1961–64. Values are expressed in °C. day^{-1} with positive values indicating convergence.

is the tendency for a second, often large, maximum of zonal available potential energy during March which occurs as the other parameters have begun their seasonal decline.

From calculations we have also estimated the atmosphere's energy cycle including the generation of available potential energy for each season and for the annual average. Figure 8 and table 2 indicate an average annual value for generation of zonal available potential energy of about 2.5 watts m.$^{-2}$ with an annual variation from about 0.5 to about 5 watts m.$^{-2}$ The generation of eddy available potential energy, on the other hand, has an average value of -0.8 watt m.$^{-2}$ with an annual variation from about -0.1 to -1.4 watts m.$^{-2}$ The conversion between zonal and eddy available potential energies has varied by as much as 25 percent from one winter to another and conceivably the zonal generation could vary by a similar amount. Presumably this is related to the strength of the meridional heating gradient, and it presents an intriguing question as to what components of the atmospheric heat balance are responsible for this difference.

Although the determination of this heating is an extremely difficult problem, it is now receiving more attention. Greater attempts are being made, for example, to collect observations of ocean temperatures and to estimate the sensible and latent heat flux into the atmosphere. The importance of the oceans as vast reservoirs of heat that is supplied to the atmosphere, particularly during fall and early winter, is well known. Of interest in this regard are the observations of above-normal water temperatures over the Eastern Pacific during January 1963 and during the five preceding months (Namias [16]). Also of interest is the effect of cloudiness, which along with snow cover has an important effect upon the atmosphere's radiation balance and may, as suggested by Lorenz [15], influence an energy cycle. Currently this problem is being attacked with satellite observations of cloudiness and radiation (Clapp [4], Winston [40]). To establish the effects of abnormalities of heating upon the general circulation, however, controlled experiments such as carried out by Phillips, Smagorinsky, Mintz, and Leith will be necessary.

Admittedly the computations we have presented here, especially the energy cycle in figure 8, leave much to be desired. Our record, while a comparatively long one, is incomplete in the vertical. In addition, it does not include the contribution from the Tropics where data are too scarce for a calculation of the eddy terms. Despite this our investigations, as well as those of Saltzman and Wiin-Nielsen, indicate that there is considerable information to be gained from energy studies of the lower troposphere using NMC data, and probably it is wise to extract as much as possible from these data before adding more levels. It should be pointed out however, that because NMC currently produces ADP analyses up to 100 mb., and also computes initial vertical velocities for two levels (650 and 350 mb) it is now possible to get a more complete vertical integration. Currently we have revised our program to include these additional levels and we are now making calculations for a deeper layer.

ACKNOWLEDGMENTS

The suggestions and interest of several of the authors' colleagues were invaluable during the course of this study. In addition thanks are due to Miss Mary Ann Ruzecki for writing the computer program upon which all the data presented here were based, and to Messrs. John Foard, John Hildebrand, and Charles Earnest who carried out numerous calculations and prepared many figures for the authors.

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[Received August 26, 1964; revised December 11, 1964]